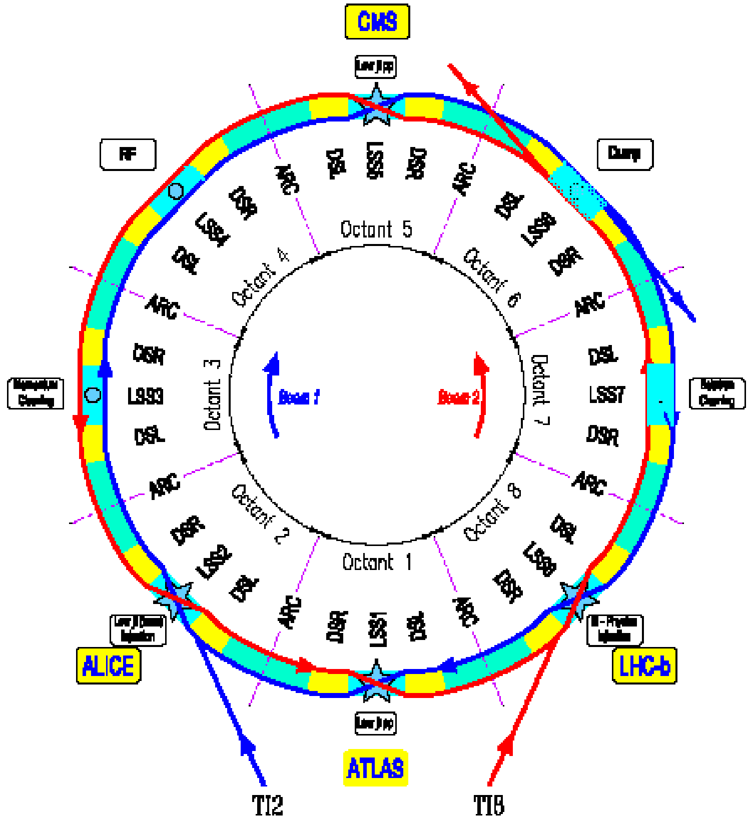
LHC IR1/IR5



- Proton beam #1 is injected clockwise at Straight 2; B2 is injected counter-CW at Straight 8.
- Beams cross between the inner & outer rings at insertions 1, 2, 5 & 8 to maintain equal path lengths.
- IR's 1 & 5 (ATLAS & CMS) are low-β (~55 cm), high luminosity (10^{34} cm^{-2}sec^{-1}) inserts with identical hardware.

IR1/IR5 OPTICAL & TECHNICAL CONSTRAINTS

- β^* MUST BE SMOOTHLY TUNABLE, FROM 18 M AT INJECTION $\rightarrow$ 0.50 M AT COLLISIONS (11M & 0.55M ALSO APPEAR IN THE LITERATURE).

- THERE ARE 14 OPTICAL MATCHING CONSTRAINTS:
  - μ_x & μ_y ARE FIXED ACROSS THE INTERACTION REGION FROM INJECTION THROUGH TO COLLISIONS (UNLIKE THE TEVATRON).
  - MATCHING AT THE IP TO: $\beta_x = \beta_y = \beta^*$; $\alpha_x = \alpha_y = \alpha^* = 0$; $\eta_x^* = 0$, AND; $\eta_x'^* = 0$ GIVES 6 CONSTRAINTS. MATCHING BACK INTO THE ARCS GIVES ANOTHER 6.

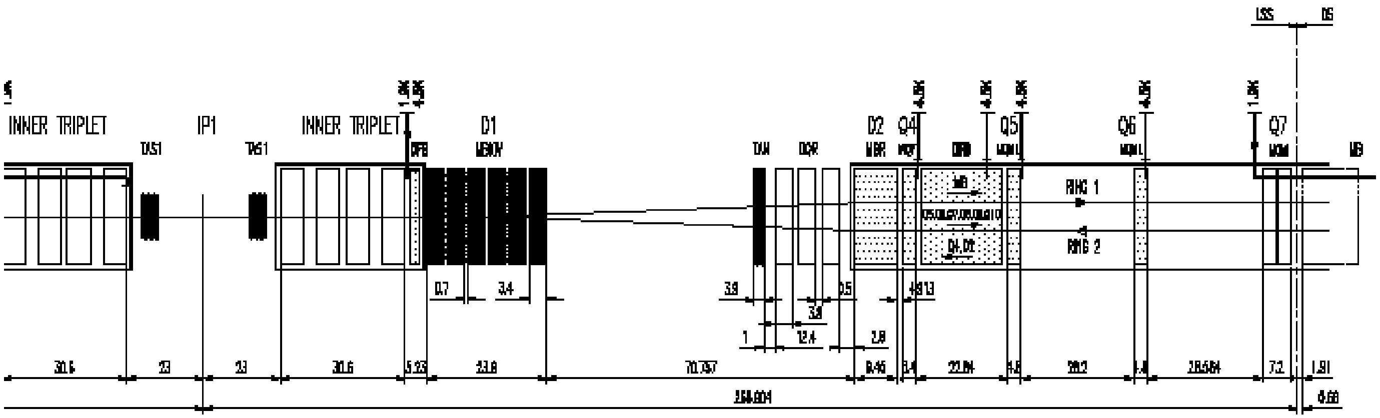
- CONTROL OF BEAM SIZE AND SEPARATION REQUIRES QUAD GRADIENTS TO VARY SMOOTHLY THROUGH THE SQUEEZE. (NO DELTA FUNCTIONS, CUSPS, OR DISCONTINUITIES ..... duh).

- INJECTION GRADIENTS AT 450 GEV MUST BE $\geq$ 3% OF NOMINAL GRADIENTS $\Rightarrow$ AT FLATTOP THE GRADIENTS BEFORE THE SQUEEZE ARE > 45% OF THEIR COLLISION OPTICS VALUES ... A HUGE CONSTRAINT ON THE IR DESIGN & OPTICS PROGRESSION OF THE LOW-β SQUEEZE.

- THE BEAM SIZE MUST FIT WITHIN THE TIGHT LHC APERTURE:
  - TRIPLET APERTURE IS DETERMINED BY β_{max} AND THE BEAM CROSSING ANGLE AT THE IP.
  - BEAM SCREENS ARE INSTALLED IN ALL IR MAGNETS.
  - OPERATIONAL APERTURE OF THE COLLIMATORS IS 7σ.
- THE DESIGN CONSTRAINT IS THAT MECHANICAL APERTURE $n \geq 7\sigma$ FOR ALL COLD ELEMENTS:

$$n^2 \equiv \left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2$$

IR Layout



- The main IR magnets span a 269 m straight section each side of the IP, with 23 m each side of the IP reserved for the detector.

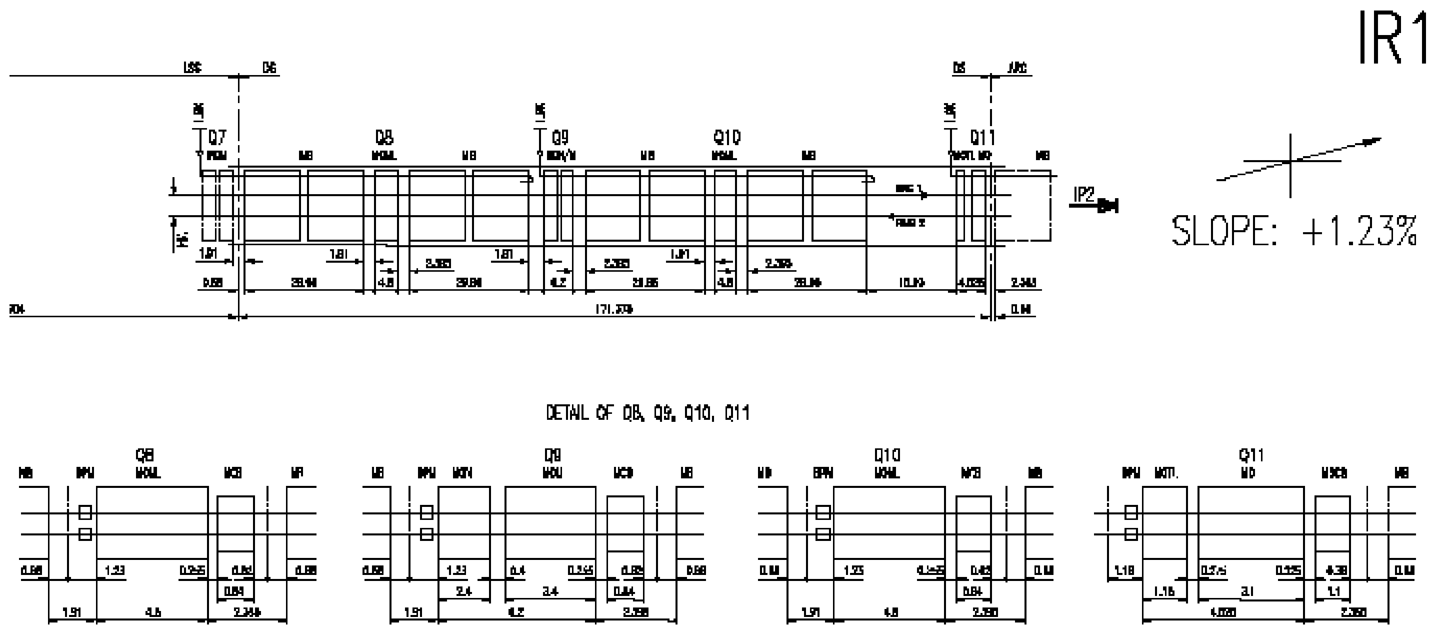
- The antisymmetric low-β triplets provide opposite focusing for the counter-rotating beams. Q1, Q2$_{A,B}$, & Q3 are single bore magnets with gradients of 200 T/m.

- D1 & D2 bring the beams together at the IP & separate them by 194 mm into separate channels by quadrupole Q4. D1 next to Q3 has a single bore and consists of six 3.4m long conventional warm magnets. 71m downstream D2 removes the beam separation angle. D2 is a 9.45m double-bore, superconducting dipole.

- Q4, Q5, Q6, & Q7$_{A,B}$ are double-bore matching quadrupoles. Q4 has a larger aperture to accommodate the IP crossing angle separation orbit.

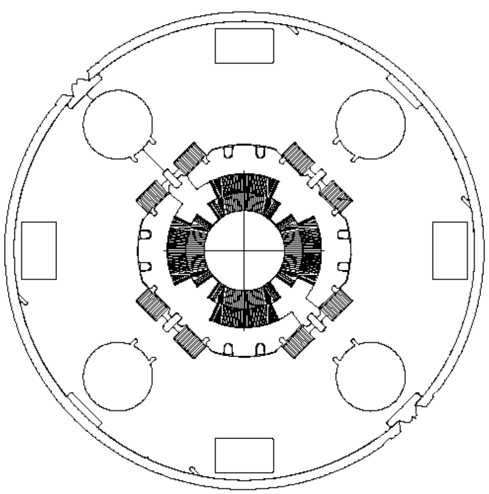
- An absorber inboard of Q1 protects the triplet & another absorber in front of D2 protects other machine elements.

Remaining IR Matching Quads

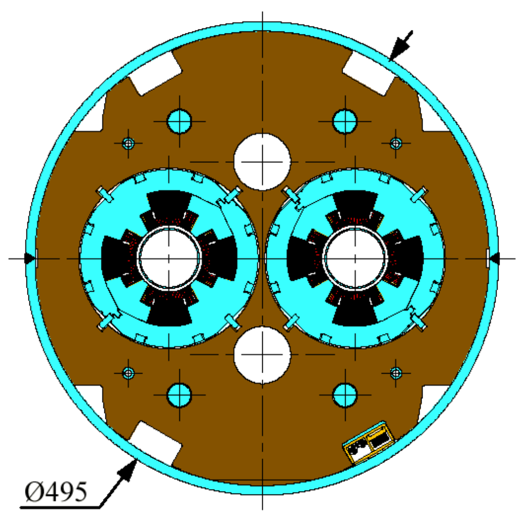


- Quads Q8, Q9, & Q10 in the dispersion suppressers are powered individually, and also the extra-long QTL trim at Q11.
- Independently-powered trims at Q12 and Q13 in the arc complete the optical match.
- Even if the triplet Q1, Q2, Q3 are powered in series, and Q4 $\rightarrow$ Q7 are powered strictly anti-symmetrically there are still 17 variable gradients to match just 14 optical constraints.

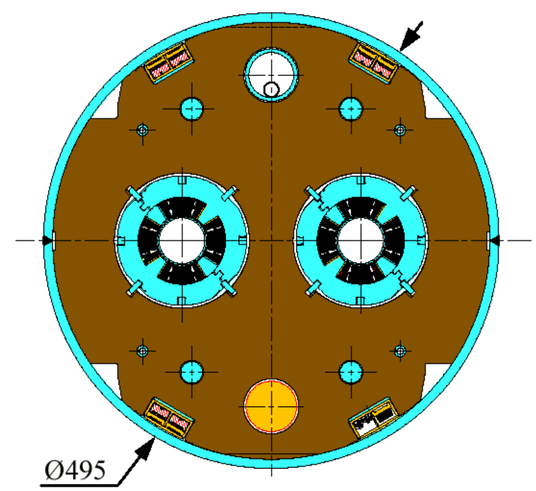
	TRIPLET			MATCHING SECTION				DISPERSION SUPPRESSOR				ARC	
MAGNET	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	QT11	QT12	QT13
#	1	2	1	1	1	1	2	1	2	1	1	1	1
TYPE MQ-	XL	X	XL	Y	ML		M	ML	M C	ML	TL	T	
L (M)	6.3	5.5	6.3	3.4	4.8	4.8	3.4	4.8	3.4 2.4	4.8	1.15	0.32	0.32
G (T/M)	200			160			200	200			110	110	
T (K)	1.9			4.5			1.9	1.9				1.9	
BORE(MM)	63			63	50			50				50	



MQX

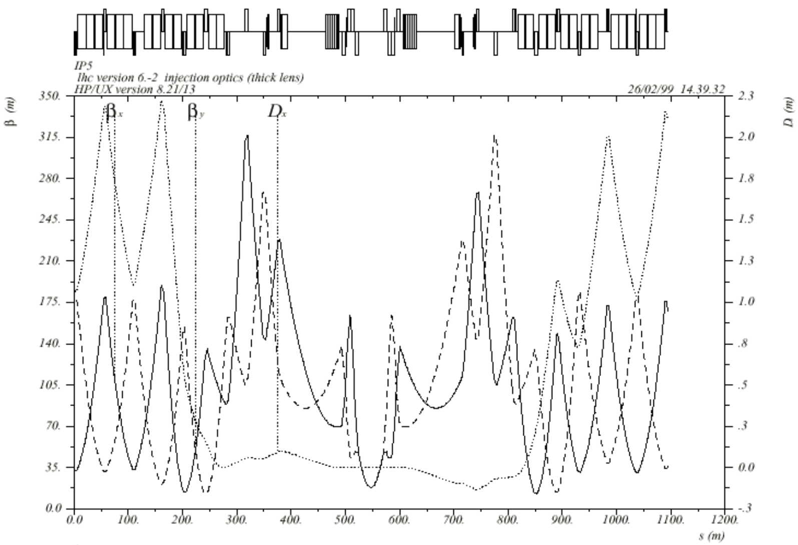


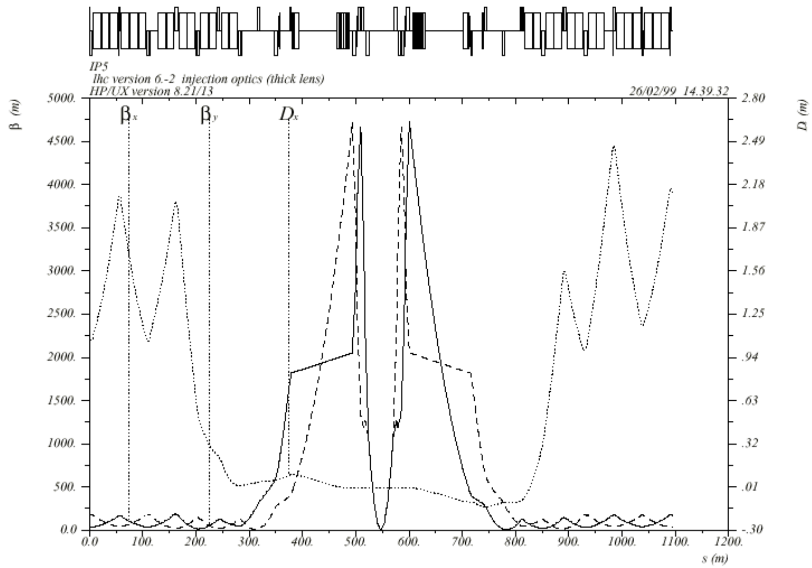
MQY



MQM

IR Optics (Beam 1)





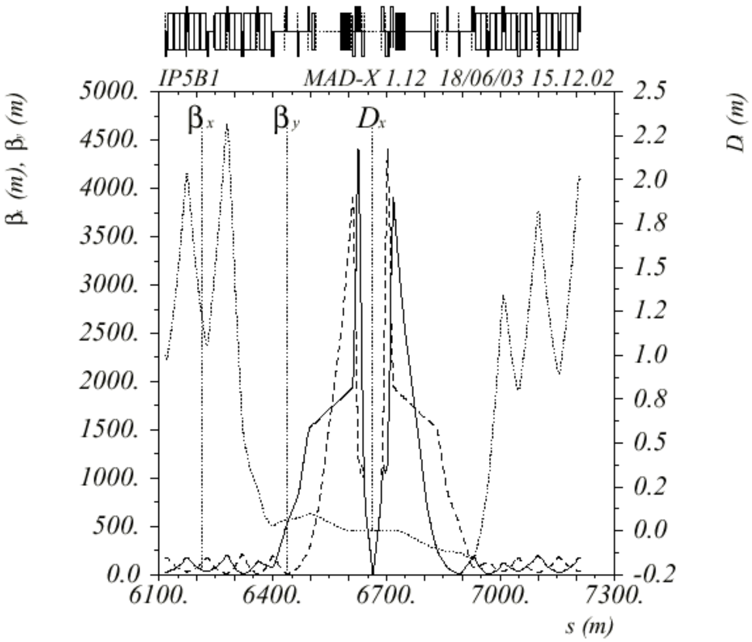
Injection

- β^* = 18.0 m
- β_{max} = 315 m @ Q6

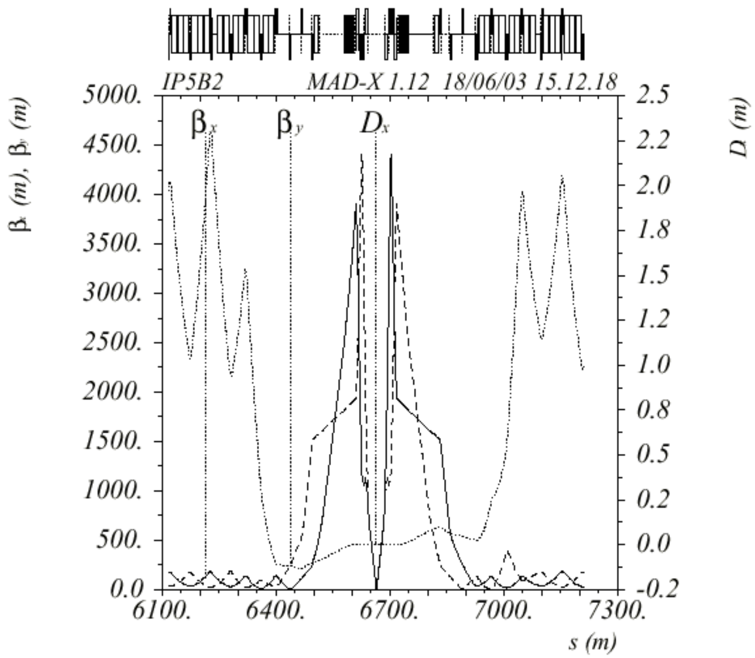
Collisions

- β^* = 0.50 m
- β_{max} = 4750 m @ Triplets

<u>COLLISION OPTICS (BEAM #1 *VS* BEAM #2)</u>

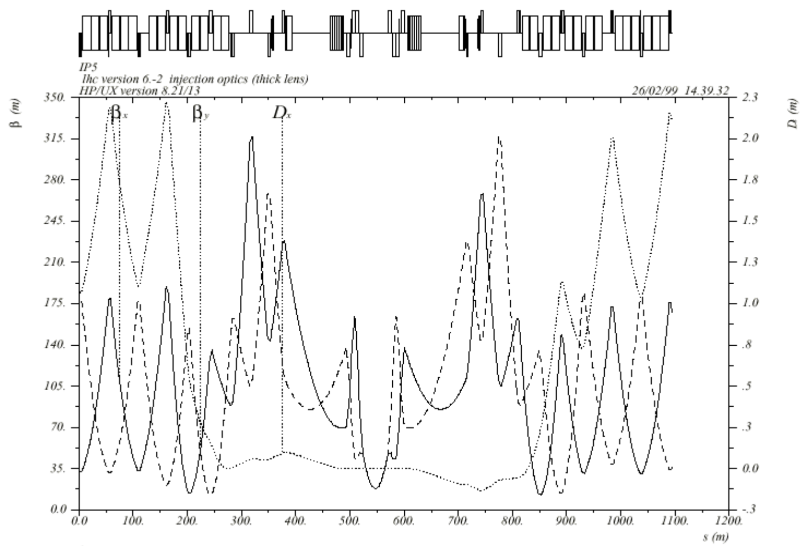


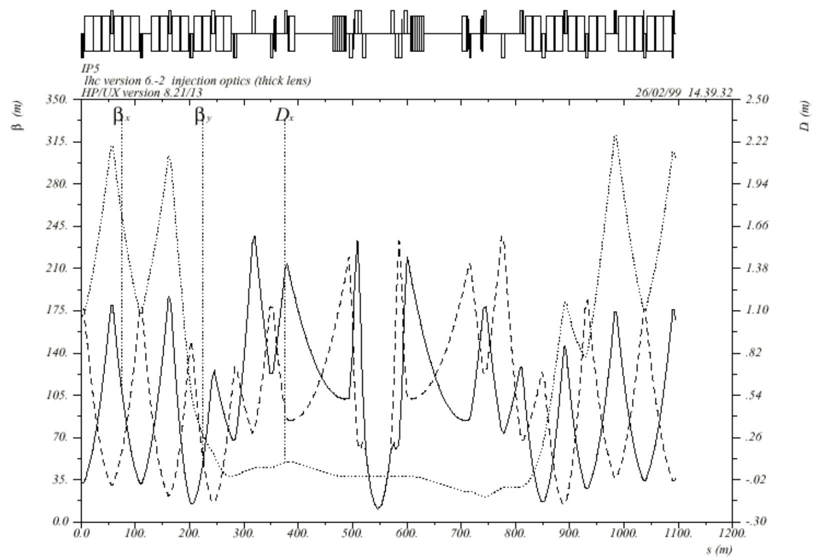
BEAM #1



BEAM #2

- RING 2 INSERTION QUADRUPOLES ARE NOT SIMPLY POWERED WITH OPPOSITE POLARITY TO THOSE IN RING 1. THIS IS BECAUSE RING 1 & 2 LATTICE FUNCTIONS ARE ONLY APPROXIMATELY ANTI-SYMMETRIC. TWO SOURCES OF VARIATIONS ARE DUE TO:
  - CROSSING OF THE BEAMS BETWEEN INNER & OUTER RINGS REQUIRES DIFFERENT GRADIENTS TO MATCH DISPERSION FUNCTIONS, AND;
  - THE LEFT & RIGHT Q8'S ARE NOT POSITIONED EQUIDISTANT FROM THE IP; *i.e.*; THE LEFT & RIGHT SIDES OF THE IP ARE NOT MIRROR IMAGES.





- β^* = 18.0 M
- β_{max} = **315** M @ Q6

- β^* = 11.0 M
- β_{max} = **230** M @ Q6 & TRIPLETS

- β^* = 18.0 M IS THE "OFFICIAL" INJECTION VALUE APPEARING IN THE LHC DESIGN HANDBOOK,

  BUT....

- β^* = 11.0 M PRODUCES A β_{max} OF JUST ~230 M [*cf.* β_{max} ~180 M IN THE ARCS] (**?**).

IR1/IR5 CROSSING ANGLE SCHEMES

- THE LIMIT ON BUNCH INTENSITY WILL ULTIMATELY COME FROM BEAM-BEAM EFFECTS. WITH 25 nsec BUNCH SPACING PARASITIC COLLISIONS OCCUR EVERY 3.75 M THROUGH REGIONS WHERE THE BEAMS SHARE A COMMON VACUUM CHAMBER. THERE ARE 15 SUCH UNWANTED INTERACTIONS EACH SIDE OF THE IP.

- CROSSING ANGLES AT THE IP ARE UNAVOIDABLE TO SEPARATE THE BEAMS RAPIDLY & LIMIT THE DAMAGE OF THESE PARASITIC CROSSINGS. FROM INJECTION THROUGH THE RAMP & LOW-β SQUEEZE THE QUASI HEAD-ON COLLISIONS AT THE IP MUST ALSO BE AVOIDED.

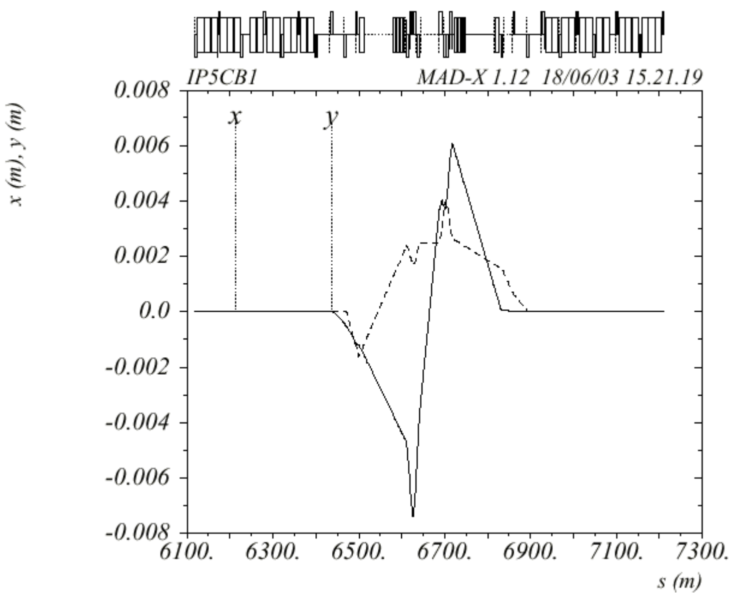
- HORIZONTAL & VERTICAL ORBIT CORRECTORS IN THE VICINITIES OF THE Q4, Q5 & Q6 QUADRUPOLES AT IP1 & IP5 ARE USED TO CONTROL THE CROSSING ANGLE & ALSO THE PARALLEL BEAM SEPARATION AT THE IP'S. AT IP1 CROSSINGS DURING COLLISIONS OCCUR IN THE VERTICAL PLANE, WHILE AT IP5 CROSSING IS IN THE HORIZONTAL PLANE.

- THE "OPTIMUM" CHOICE OF CROSSING ANGLE IS A COMPROMISE – BEAM-BEAM EFFECTS REDUCE WITH INCREASING σ'S OF SEPARATION, FAVORING A LARGE θ; BUT BEAMS TRAVELING OFF-AXIS THROUGH THE TRIPLET CONSUME APERTURE & EXPOSE THE BEAMS TO POOR FIELD REGIONS, BOTH EFFECTS FAVORING A SMALL θ. FURTHER, LUMINOSITY DECREASES WITH CROSSING ANGLE AS:

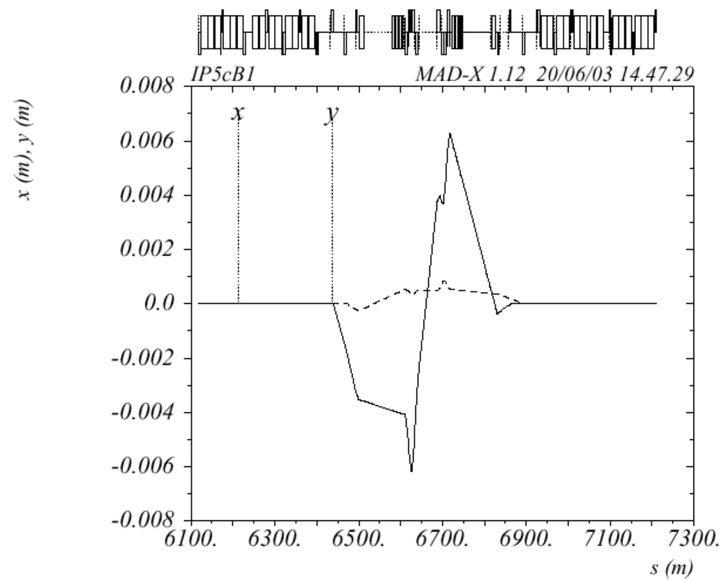
$$F \approx \left[1+\left(\frac{\sigma_z\theta}{\sigma_x^*}\right)^2\right]^{-1/2}$$

STATE	β^* (m)	HALF CROSSING θ_H (μrad)	VERTICAL ORBIT (mm)	SEP $_{IP}$ (σ)	SEP $_{min}$ (σ)
INJECTION	18.0	160.0	2.50	13.3	10.5
RAMP	18.0	40.0	0.625	13.3	10.5
PRE-COLLISION	0.55	142.5	0.50	60	6.9
COLLISION	0.55	142.5*	0.0	0.0	6.9

* θ_H = –142.5 μrad & ε_X = 22.5 μm (95% normalized) gives 9.4σ separation at the 1st parasitic crossing, but drops to a minimum of 6.9σ at the 10th crossing.
Luminosity reduction factor $F(\theta_H)$ = 0.84 for σ_Z = 0.0755 m.

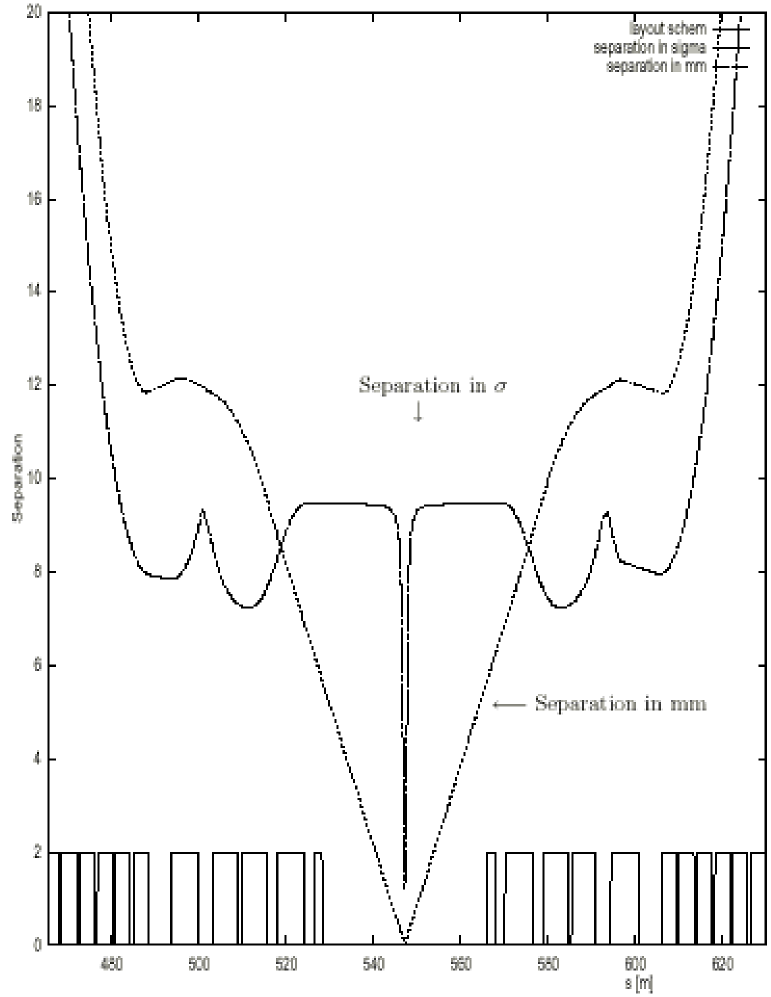


- 450 GEV INJECTION B1 ORBIT AT IP5.

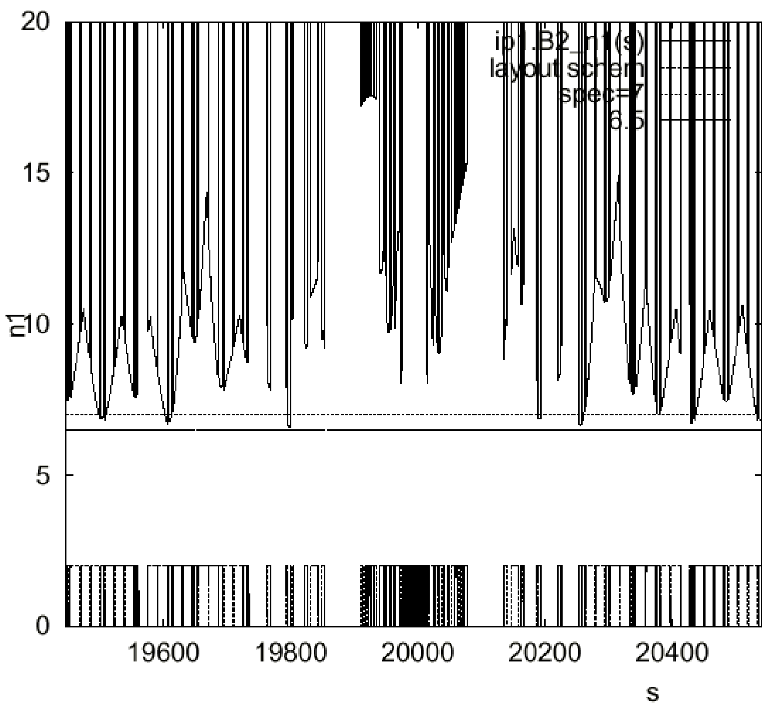


- 7 TEV PRE-COLLISION B1 ORBIT AT IP5

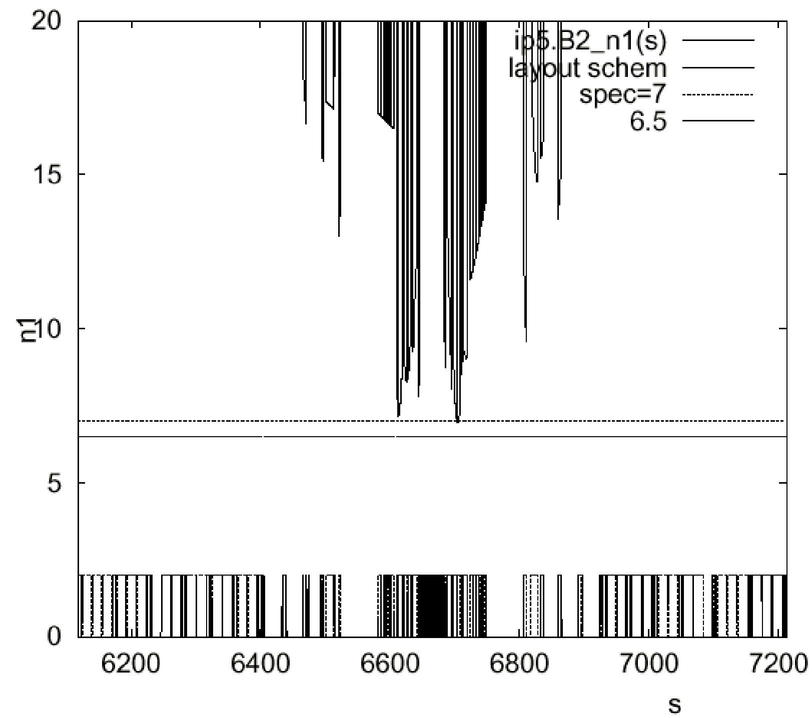
BEAM SEPARATION AT IP5 DURING COLLISIONS
(β^* = 0.55 M)



MACHINE APERTURE MEASURED IN BEAM σ



- 450 GEV APERTURE FOR β^* = 18 M INJECTION OPTICS EXTENDING THROUGH THE DS CELLS LEFT & RIGHT OF THE IP.



- APERTURE AT 7 GEV DURING COLLISIONS WITH β^* = 0.55 M.

Ω